Renewable Energy 87 (2016) 1023–1030

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A methodology for optimization of the complementarity between small-hydropower plants and solar PV systems

Ioannis Kougias*, Sándor Szabó, Fabio Monforti-Ferrario, Thomas Huld, Katalin Bódis

European Commission, Joint Research Centre, Institute for Energy & Transport, Renewables & Energy Efficiency Unit, Via Enrico Fermi 2749, IPR45, 21027, Ispra, Italy

ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form
11 September 2015
Accepted 30 September 2015
Available online 21 October 2015

Keywords:
Renewable energy sources (RES)
Complementary RES
Optimization
Hybrid
Small hydropower

ABSTRACT

Key global energy, environmental and sustainability targets are closely related to the development of Renewable Energy Sources (RES). This includes reduction of Greenhouse Gas emissions and safe energy provision in a sustainable manner. The integration of RES in the energy mix needs to overcome the technical challenges that are related to grid's operation. Therefore, there is an increasing need to explore approaches where different RES will operate under a synergetic approach. A straightforward way to achieve that is by optimizing the complementarity among RES systems both over time and spatially. The present article developed a methodology that examines the degree of time complementarity between small hydropower stations (SHPS) and adjacent solar PV systems (SPVS). The methodology builds on an optimization algorithm that associates hydrological with solar irradiation information. In particularly, the algorithm examines possible alterations on the PV system installation (azimuth, tilt) that increase the complementarity, with minor compromises in the total solar energy output. The methodology has been tested in a case study and the outcome indicated that a compromise of 10% in the solar energy output (90% threshold) may result in a significant increase of the complementarity (66.4%).

1. Introduction

1.1. Regulatory framework for RES electricity

The recent 5th Assessment Report published by the Intergovernmental Panel on Climate Change (IPCC) suggests that decarbonization of the energy supply sector requires up-scaling of low- and zero-carbon electricity generation technologies [1]. Moreover, in the special report on Renewable Energy Sources (RES) and climate change mitigation [2] IPCC has underlined hydropower's significant potential for carbon emissions reductions. Furthermore, it has provided evidence showing that relatively high levels of hydro-deployment are expected over the next 20 years and hydropower should remain an attractive RES within the context of global GHG mitigation scenarios. The direction on utilizing the available hydropower potential has also been supported in the United States of America through an Act approved by the Senate and the House of Representatives [3].

In October 2014 the European Council agreed on the *2030 Climate and Energy Policy Framework* setting EU-wide targets for the period between 2020 and 2030 [4]. These targets aim to result in a more secure and sustainable energy system in the EU, meeting the 2050 greenhouse-gas (GHG) reductions target. Apart from a 40% reduction in GHG emissions and a 30% improvement in Energy Efficiency, the 2030 EU-wide targets set a minimum of at least 27% share of RES in the energy consumption. This latter target sets the minimum level of RES in 2030 moving forward from the previous 2020 target (20%). Notably, the transition from a country-level targets to an EU-level target offers more flexibility to the implementation of projects and the deployment of RES systems. Therefore, the optimal combination of low-carbon energy sources in the energy mix will become even more important.

1.2. Status of RES development

Considering both the technical challenges and the current economic status of the energy market, it is safe to say that innovative solutions will be required to support the deployment of additional RES capacity. Ingenious system-design and optimal RES' planning are required to support installation in the current economic environment that is characterized by limited economic resources for

* Corresponding author.
E-mail address: Ioannis.Kougias@ec.europa.eu (I. Kougias).

http://dx.doi.org/10.1016/j.renene.2015.09.073

Nomenclature

RES	Renewable Energy Sources
SHPS	Small Hydropower Station
PV	Photovoltaic
SPVS	Solar PV System
CSP	Concentrating Solar Power
GHG	Greenhouse Gas

investment. Such novel approaches will result in energy systems that support safe energy production, involving variable RES in a significant and increasing share. Integration of higher shares of RES in the energy portfolio calls for technologies and techniques to manage load demand fluctuations and optimal operation of reserve capacities. As the presently applied techniques (storage capacity, curtailment and reserves in responsive power) imply either additional costs or the partial loss of the energy output, other solutions are worth to be investigated. In that sense, optimization of the complementarity between different intermittent sources could be a primary choice in which an optimal trade-off between the overall amount of energy produced and its time stability is aimed.

The current research presents such an approach, aiming to utilize the complementarity between two RES, small-scale hydropower stations (SHPS) and solar PV systems (SPVS). In a recent research conducted by the authors [5] it was illustrated that European water bodies offer a significant potential for mini- and small-hydropower stations' deployment. Building on their experience on the complementarity between wind and solar RES [6], the authors explore in the present research the possibility to link the design of solar-systems with the operation characteristics of adjacent hydroelectric stations.

In the present article the term complementarity refers to the extent that energy output from different RES is not correlated over time. Such a complementarity aims to reduce the intermittency of energy production, by combining systems that have their min/max energy output in different time periods. The combination of such 'asynchronous' energy production systems is evaluated using the Pearson correlation coefficient. Accordingly, this coefficient is calculated by comparing the energy output of two specific energy production systems over time. Its value ranges between -1 and 1 and low, negative values indicate anti-correlation in the energy output and time complementarity of the two systems.

2. Integration of RES in existing systems: limiting factors

Following the policy directives, and the societal-economic pressures described in the previous section (§1.2), the integration of RES is a priority for several countries. Nevertheless, the integration of a variable renewable power generation into existing power systems is known to have consequences on the systems' operation and their future expansion [7].

Indeed, the temporal variance of RES energy production is imposing significant challenges for the system operators, who need to ensure that energy grids will continuously respond to demand. This can be further hampered by the often significant-quantities of spilled energy. For this reason, several scientists have focused their research on forecasting the energy production from RES and assessing its variability. Currently, renewable power generation is typically directed to the main grid and is combined with the power produced by conventional systems (e.g. coal, gas, nuclear). The resulting energy mix is then distributed to consumers. However, as RES are expected to become dominant element of the electricity generation portfolio, this approach exposes system-level weaknesses.

Therefore, the development of ingenious RES systems that will 'smoothen' the intermittent energy production is a key point in ensuring the sustainability of future energy systems. This subject has attracted the interest of both the scientific community and the industry. Accordingly their efforts have been directed towards the development of systems with advanced efficiency, taking advantage of technological advances and hybrid operations in the concept of smart-grid design.

2.1. Integrated approach to address the challenges

In the present research the authors explore the time complementarity between two RES systems (solar PV and small hydro) and whether it can be optimized by adjusting the installation characteristics of the SPVS. In sections §4 and §5 the authors present a methodology that assesses and maximizes (optimizes) the aforementioned anti-correlation through the development of a specifically tailored algorithm.

The developed approach relies on alterations to the PV-systems' design, aiming to even the total energy production, rather than increasing the specific PV production. This is equal to 'smoothing out' power production and decreasing the instances of high and low values of electricity production. As a result the predictability of the energy production will be improved, supporting the mitigation of under/over energy production of RES systems [8]. By making the energy production less stochastic not only provides stability to the grid but also decreases the dependence on high-cost energy storage systems (e.g. pumped storage).

2.2. Background: literature review

As Renewables' deployment developed, scientists examined the possibility to combine different RES in order to improve the overall system efficiency. Such an analysis can in principle be performed for both a specific geographical location or involving a wider area such as a country or a continent, while in most cases the literature research focused on stand-alone systems in developing countries, where connection to the grid was either impossible or too costly.

2.2.1. Complementarity of stand-alone systems

While not designed for grid injection, stand-alone systems share with the objective of the present paper an optimization target, related to minimizing the dependence on costly battery storage or fossil fuels and developing mini-grids that provide electricity in an uninterrupted manner.

Accordingly, the authors of [9] examined the different options for a stand-alone system, minimizing the dependence on battery storage and diesel gen-sets. In Ref. [10] the authors examined the possibility of hydrogen energy storage in a hybrid PV-Hydro system in the Alps, also including in their analysis a comparison between the performance of the hybrid system to common PV-system installation. The authors of [11] developed a method for the optimal design and operation of a stand-alone hybrid system (solar PV, hydro, wind) that aims to minimize backup fossil-fuel consumption. The application in a community in India evaluated the different combinations of RES. In Ref. [12] a similar research has been conducted for a community in Cameroon, where a hybrid hydro and solar PV system were coupled by a bio-gas generator in order to provide electricity in a continuous manner. Bekele and Tadesse [13] optimized a hybrid hydro/PV/wind station in a rural community of Ethiopia.

2.2.2. Spatial analysis of complementarity

Moving towards more spatially dispersed generation systems, Beluco et al. have been pioneers in analyzing the complementarity between hydro and solar PV [14]: they have distinguished space complementarity from time complementarity and introduced the complementarity index of a given place. Their case study in Rio Grande do Sul, Brazil indicated areas of high complementarity while in their later research [15], they have analyzed the performance of a hybrid hydroelectric solar PV station and how the complementarity of the two sources is connected to failures on electricity provision.

It is clear that research apart from focusing on the design–operation of hybrid systems, should also provide a road-map for Renewables' combination in a holistic way, where the complementarity of different RES would be maximized. Recognizing this necessity scientists have only recently directed their efforts on such a holistic approach, where spatial analysis supports the optimization of synergetic RES installations. Notable is the work of [6] who analyzed the spatial complementarity between solar PV and wind in Italy. Following a Monte-Carlo approach, the research estimated how probable is for solar PV and wind energy production to be complementary in different places in Italy. Similar is the objective of [16] who evaluated the combination of wind power and concentrating solar power (CSP) and whether this combination can produce stable or even base-load power. The investigation highlighted the existence of certain locations in Spain where there was spatio-temporal balancing between wind and CSP. Their research has been extended in a recent study [17], where they spatially analyzed RES sites in the Iberian Peninsula, indicating that to some extent-wind and solar RES are complementary to each other. The long-term correlation between wind speed and solar irradiance has been studied in Refs. [18], selecting an island in Brazil as a case study.

3. Complementarity between RES: the role of small hydropower

Section 2.2 revealed that a number of scientists have examined the complementarity between wind and solar. However, in the current literature there is a gap on similar analysis between hydroelectric and solar energy. Building on our recent research work we examine in the present study the temporal inter-dependency between solar and hydropower.

3.1. Hydroelectric renewable energy production

SHPS are regarded as a RES due to their minor environmental impact. The current study focus on SHPS that only have negligible storage capacity or they are in the run-of-river. Therefore, their installation doesn't require dam construction and the subsequent flooding of surrounding areas. Such SHPS have limited (or no) water storage capacity and do not rely on typical reservoir operation practices [19], [20]. Accordingly, the energy production basically depends on the streams' water discharge. Obviously, this characteristic of the SHPS is beneficial for the environment, but also reduces the flexibility of their operation. Thus, SHPS' energy production is proportional to the river flow and follows its variability. Their design power capacity is calculated from Eq. (1) [21]:

$$P = n \times \rho \times g \times Q \times H \tag{1}$$

where P: available power (W), n: turbine's efficiency, ρ: density of water (kg/m^3), g: gravity acceleration, Q: water flow (m^3/sec), H: available hydraulic height (m)

The net hydraulic head H in the studied SHPS doesn't vary

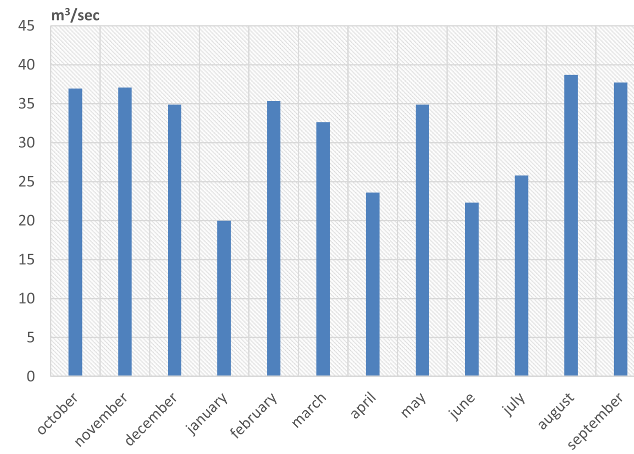


Fig. 1. Mean monthly water-flow in the studied SHPS.

significantly in a seasonal basis, because of the absence of dam. The amount of stored water (if any) is limited and the height difference between its surface and the turbine's outlet is almost constant. On the contrary, water discharge Q (Eq. (1)) fluctuates throughout the year with these variations in flow affecting the turbine's efficiency n. According to the turbines' operation curves, efficiency doesn't vary significantly under typical flow conditions. These curves aren't identical among the different types of turbines but they have a common characteristic: the turbines' efficiency drops significantly when Q takes very low values (e.g. dry summer) and remains constant under typical flow conditions.

Fig. 1 illustrates monthly values of the water discharge in a location that served as a case study for the present research. Values of the measurements for the year 2014 have resulted to Fig. 1. Such measurements are typically used by scientists and developers to estimate the expected inflow into SHPS and the corresponding energy production.

The scope of this research is to analyze the degree of complementarity between SHPS and SPVS based on monthly electricity energy production. In the case of run-of-river SHPS (like the one studied in this research) water discharge usually does not show large variability on the hourly scale and as a result this time scale is not relevant to the investigation we are performing. For SHPS that also have water storage capacity, reservoir management needs also to be considered. In such cases inflow to the turbine is determined not only from the water availability but also from other parameters (e.g. energy demand, energy price, subsidies). The authors have analyzed the optimization of the operation of a hydropower dam in a recent research, where hourly load profiles have also been taken into account [22].

3.2. Estimation of solar irradiance – solar energy potential (PVGIS)

The estimation of the output of the PV-system has been achieved with the use of the interactive web-based tool *PVGIS*[1] that has been developed at the *Renewables & Energy Efficiency Unit, JRC*.

The estimates of PV power production are based on solar radiation data from the Satellite Application Facility on Climate Monitoring (CMSAF[2]). The methods for estimating the solar radiation at ground level have been described in Refs. [23] and [24]. Using these

[1] PVGIS Available online at: http://re.jrc.ec.europa.eu/pvgis/.

[2] Website: http://www.cmsaf.eu.

algorithms, global horizontal and direct normal solar irradiance values have been calculated for an area covering Europe and Africa with a spatial resolution of 0.025° latitude/longitude.

Data on air temperature have been taken from the ERA-interim reanalysis of the European Centre for Medium-range Weather Forecast (ECMWF[3]).

The calculation of the output power of a PV system at a given location can then be performed in the following steps:

1. From the global and direct irradiance values the global irradiance in the plane of the modules is calculated using the model of Muneer [25]. A correction is made to account for the reflectivity of the PV modules at sharp angles of incidence, according to Martin & Ruiz [26].
2. From the in-plane irradiance, the ambient temperature and the wind speed, the PV module temperature is calculated according to the model of Faiman [27], using the coefficients determined for crystalline silicon modules [28].
3. The PV array output DC power can then be calculated from the in-plane irradiance and module temperature using the model presented in Ref. [29].

3.3. Early indications of complementarity

Complementarity of intermittent resources supports the overall power system, because optimally designed SHPS and SPVS can cover at least some of the cost of energy storage [6]. Besides, the potential to develop a synergy between solar and hydro systems is supported by the assumption that in some areas (e.g. Mediterranean countries) river-flow decreases during summer, when solar irradiance has its maximum annual values (north hemisphere).

By inserting the inflow values of Fig. 1 to Eq. (1) it is possible to estimate the SHPS's expected energy production in future months. Since the present study focus on stations with negligible water storage capacity, the energy production is proportional to the natural flow. Matching SHPS's output estimations to the expected energy production of a SPVS in the area results in Fig. 2.

Fig. 2 offers an initial indication that on the studied location the energy production from the two RES is not complementary. Indeed, energy produced by the SHPS has a low peak during the winter months when solar production has its lower production. At the same time water discharge and the consequent hydropower production have their annual maximum in August, when solar energy production is significantly increased. The solar PV energy output in Fig. 2 corresponds to an 'optimal PV-system installation', which is equal to setting the system in an azimuth and inclination that maximize the expected annual solar energy output.

Studying the complementarity between solar and hydro arises the following questions:

1. How complementary are the two RES?
2. Is it possible to increase their complementarity?
3. Does this complementarity appear in a similar way to other/all locations?

The aim of the present study is to investigate these questions. In order to achieve that, an algorithm has been developed and the resulting tool aims to facilitate the inclusion of complementarity as a parameter in the planning of future PV systems. The characteristics of this tool along with its functionalities are presented in detail in the following section.

[3] Website: http://www.ecmwf.int.

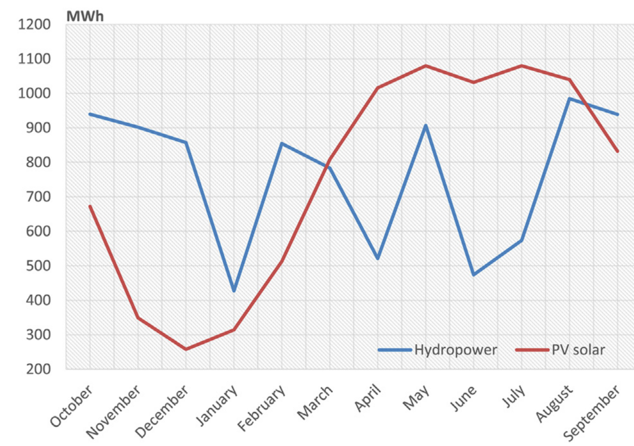


Fig. 2. Expected monthly energy production.

4. Model formulation – development of an algorithm

The developed algorithm is applicable to any geographic location and thus it can examine the degree of complementarity between different systems in various places. Following the input of the required information, the algorithm calculates the complementarity of hydro to solar. Eventually, the algorithm examines possible alterations in the SPVS installation and through an optimization process suggests solutions that are maximizing the overall complementarity.

Input data include geographic information on the location and hydrologic information on the discharge–inflow to the SHPS. These measurements take into account residual flow requirements (environmental flow), while calculating the expected monthly energy production of the SHPS. Subsequently, the algorithm processes solar irradiance information for the surroundings of the SHPS, using PVGIS.

It is well known that the orientation and the inclination (tilt) of any solar PV installation affects the energy output [30]. Thus, if the PV modules are installed towards a direction and in a tilt that maximize the received solar irradiance, the energy output is maximized. These characteristics of orientation and tilt define the *optimal installation*.

Initially, the algorithm calculates the anti-correlation between the monthly energy production from SHPS and the SPVS. This calculation is made under the assumption that the SPVS's setting is *optimal*. Subsequently, an iterative optimization algorithm examines possible variations in the installation characteristics of the solar system, aiming to increase the complementarity.

4.1. Compromising energy output for increased complementarity

The rationale behind the developed methodology is that a slight divergence from the optimal PV system installation can be beneficial for its complementarity to the SHPS energy production. In that way a small reduction in the SPVS energy output will have a positive impact on the complementarity between the two RES. Generally, the bigger the compromise we are willing to accept the higher the increase to complementarity.

4.2. Description of the developed algorithm

Every optimization process aims to detect those values of the decision variables that optimize the objective function that describes the benefits derived from alternative solutions. In Fig. 3 the optimization algorithm is illustrated in detail.

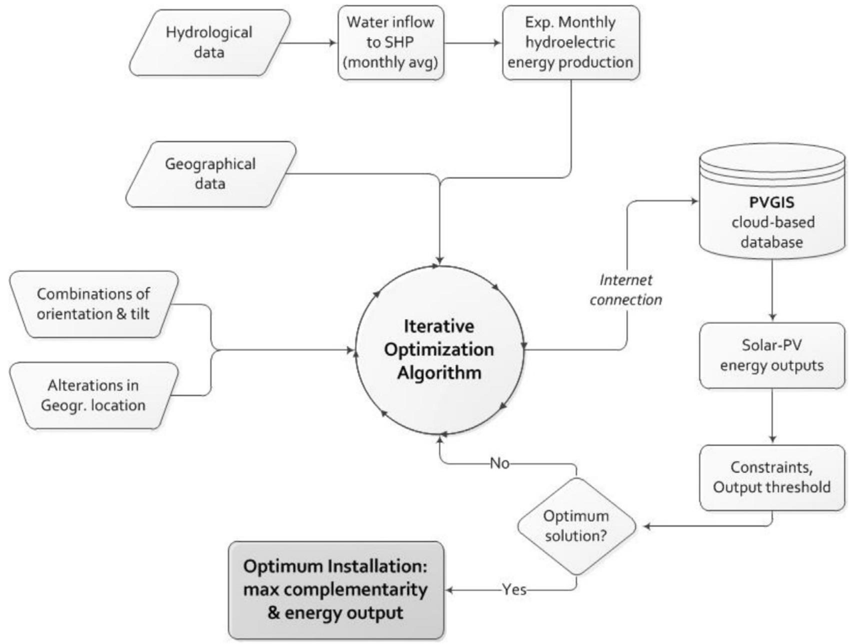


Fig. 3. Flowchart of the developed methodology: Optimization process.

4.2.1. Input parameters

Initially the algorithm analyzes the operation of the SHPS. Hydrologic information and streamflow measurements are processed and the average monthly discharge available for hydroelectric energy production is calculated. Consequently, the expected energy output of the SHPS is calculated for every month of the year. Geographical information refer to the location of the SHPS. SHPS and SPVS need to be close to each other in order to form an integrated system. Therefore, the location of the SHPS guides the selection of suitable positions for the SPVS.

4.2.2. Decision variables

Decision variables in the developed model are the values of the orientation (azimuth) and inclination (tilt) of the SPVS to be installed near a SHPS. The model has also the ability to examine alterations in the geographic location of the PV installation (not in the scope of the present research). Thus, it can examine locations in the vicinity of the SHPS, that favor the total system's complementarity and energy output.

The developed algorithm analyzes all possible combinations of the decision variables orientation and inclination of the SPVS. This includes analyzing all possible azimuth values from 0° to 360° as well as SPVS with a tilt ranging from horizontal (0°) to vertical (90°). Both decision variables are analyzed with a step of 1° with the total number of possible combinations being 32,400 (360 × 90).

4.2.3. Iterative optimization process

Then, the *brute-force* process is executed iteratively. The optimization technique has been developed in MATLAB environment and performs an *exhaustive search*. That approach was selected because the solutions' search space is confined and the optimal solution can be detected in short computation time.

Each installation option (combination of orientation and tilt of the SPVS) is a candidate solution. For each candidate solution the algorithm makes a query to the PVGIS server and through an internet connection it inquires solar energy information stored at the online PVGIS server. Subsequently, PVGIS server provides the *average global irradiance per* m^2 received by the modules of the candidate system configuration (kWh/m^2) and the *average daily and monthly electricity production* of the given system (kWh), both for every month of the year.

The expected annual energy output of candidate solutions is then compared to the hypothetical annual energy output of the *optimal installation*. The user imposes a threshold on the compromise that is willing to make in order to increase the complementarity and this acts as a constraint. Obviously, the threshold for the *optimal installation* is 100%.

Following that, the solar output of the candidate solution is compared to the corresponding output of the SHPS and the Pearson correlation coefficient between the two datasets is calculated. Obviously, the lower the value the better the complementarity between the two RES systems. Finally, as soon as all possible installation options are analyzed and the iterative process is completed, the candidate solution that maximizes the anti-correlation without violating the energy threshold is selected.

This iterative optimization process is repeated several times, for different values of the threshold in order to explore the possible gains in complementarity. As it is presented in §5.1 (Table 1), in the present research we have analyzed 7 different threshold values.

5. Application of the developed methodology

The developed methodology has been tested using stream flow measurements (Sárvár gauging station) and the hydrologic data of Fig. 1 correspond to the discharge that is expected to flow – on average-into a SHPS that is operating in west Hungary (*Latitude* = 47.385, *Longitude* = 17.036). The SHPS is named Kenyeri and was a part of a development project titled 'Small Hydro Power Plant on the Rába river'. It has a net hydraulic head of 4.4 *m* and operates a Kaplan type turbine with a design maximum discharge of $Q_{max} = 40\ m^3/sec$. The turbine's efficiency ranges throughout the year from 0.75 to 0.9, depending on the inflow. Accordingly, the power capacity of the SHPS is $P = 1500\ kW$ (Eq. (1)) and the average annual energy production is ≃9000 *MWh*.

Fig. 2 illustrates the expected monthly renewable energy production both by the 1500 kW SHPS and from a SPVS if installed in

Table 1
Complementarity between hydro and solar for different levels of energy-output compromise.

Options	Energy threshold	Correlation coeff.	Change	Azimuth	Inclination
Optimal	100%	−0.101		0°	35°
1	99%	−0.119	−18.0%	−7°	27°
2	97.5%	−0.132	−11.5%	−5°	21°
3	95%	−0.148	−11.9%	−8°	14°
4	92.5%	−0.159	−7.2%	−11°	9°
5	90%	−0.167	−5.4%	−27°	6°
6	87.5%	−0.177	−5.7%	−74°	6°
7	85%	−0.181	−2.2%	−106°	5°

the vicinity of the SHPS (*Latitude* = 47.383, *Longitude* = 17.040). In order to enable comparison of the complementarity of the two RES and considering the higher capacity factor of SHPS compared to SPVS, the conceptual PV system has been assigned a capacity of 8 MWp.

As described in Section 4.1 the proposed methodology examines options of compromising a proportion of energy output in order to increase the complementarity between the two systems. Obviously, a significant reduction in energy production is neither a sustainable nor acceptable option. We have tested the methodology for a range of values of compromise (thresholds) in order to examine in depth the interrelation of the two RES.

5.1. Range of compromise in energy output

The developed model-algorithm was run setting the values of the energy output constraint (threshold) between 85–99%. The outcome of these runs is illustrated in Table 1. As expected the bigger the compromise we accept the highest the increase to the complementarity.

The optimal PV-system installation has a small initial complementarity with the SHP, indicated by the value of the correlation coefficient (−0.101). This value of anti-correlation is equal to a solar system being installed independently from the existence of the SHP, with the installation-design aiming to maximize the solar PV output. In the area under study the optimal installation faces south (azimuth = 0°) and has an inclination of 35°.

Reading the results of the simulations in Table 1, it is interesting that initially small energy compromises result in noticeable increases of the anti-correlation (options 1–3). Thus, a first compromise of 1% on the total production (from 100% to 99%) has a significant impact to the complementarity (≃18.0%). However, further increases of the complementarity require larger 'sacrifices' on the energy production. Eventually, option 7 (threshold = 85% of the max energy production) is a convergence point, where a further compromise benefit the complementarity only by 2.2%. In the area under study that point corresponds to a system's complementarity with a correlation coefficient equal to −0.181.

Fig. 4 illustrates the relation between gains in complementarity and compromises in solar PV energy output. The curve is initially steep, gradually becomes smoother and eventually becomes horizontal at the convergence point. This curve represents the trade-off between complementarity and solar energy output for the specific location and can be a valuable tool for decision-makers while setting the threshold level in the planning phase of similar projects.

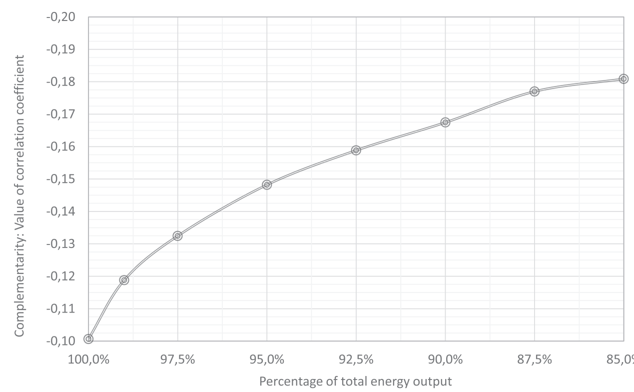


Fig. 4. Trade-off between energy output and complementarity.

5.2. Influence on the PV-system's azimuth-inclination

It is interesting to analyze the changes in the azimuth/inclination on installations that favor complementarity. Analyzing the values of Table 1, it appears that for the studied system, the complementarity of the two RES increases with the solar PV installation facing towards the east and the tilt decreasing. At the convergence point (threshold = 85% of the optimal output) the PV-system is installed in an almost horizontal position (*tilt* = 5°) and faces to east (azimuth = −106°).

The atypical tilt is the trade-off of the gains that the optimization method favors to increase the summer production and allow for losses in winter. This tilt is not usual but with the dramatic PV price reduction the gains in integration cost or complementarity can justify part of the losses in production.

5.3. Level of energy output compromise

Selecting a level of compromise is a complex issue that is not an objective of the present study. It requires a site-specific techno-economic analysis, where decisions will be based on various parameters such as the existence/type of incentives, the cost of energy storage and others. 'Sacrificing' significant quantities of energy output is a questionable practice, especially considering that after a certain point increases might be negligible (see Table 1, option 7).

Fig. 4 and Table 1 give some insight on the trade-off between the solar PV energy production and the complementarity with the SHPS. For the present study it appears that setting the threshold at 90% is a reasonable practice: the complementarity is significantly increased and the 'sacrifice' of energy production is limited. The 90% threshold results in a deviation from the 'optimal' PV system installation. Thus, instead of an installation facing south and tilted at 35°, the PV-system needs to be turned 27° from south towards the east and tilted at 6°.

In Fig. 5 the expected monthly energy production of the two installation options (threshold set to 100% and 90%, respectively) is illustrated along with the trend of SHP's energy production. It appears that for the studied area complementarity over time is increased as the PV-system's output increases in summer. Indeed the '90%' option results in increased energy output in May, June and July. At the same time significant reductions in the energy output

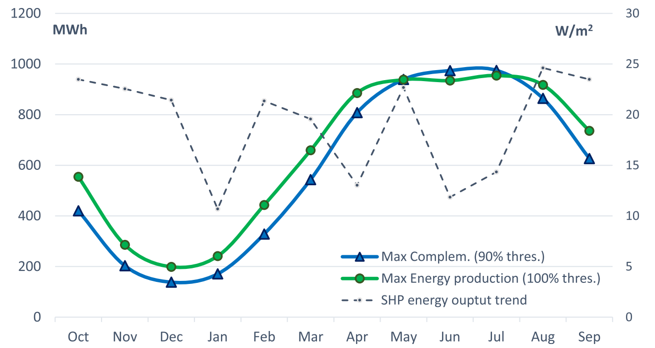


Fig. 5. Global irradiance for two solar PV installation options (W/m^2) projected over the SHPS output (MWh).

appear in the rest of the year. These latter reductions are equal to ‘smoothening’ the peaks of PV's energy production and can be connected to the issue of non-dispatchable energy production.

It appears that designing the PV-system in such a way that a proportion of winter energy production is ’relocated’ to summer is beneficial for the system's complementarity to SHP. Obviously, this ’relocation’ comes with a price, i.e. a 10% reduction in the overall production. The optimal level of trade-off between the PV output and complementarity between PV and hydro generation depends on the costs of ancillary services or storage. Finding this level is not the scope of this study, but as storage capacities are usually quite expensive (can add up to 40% of the overall cost in off-grid systems) a 10% loss in productions can be considered a reasonable price to pay.

5.4. Daily energy output profiles

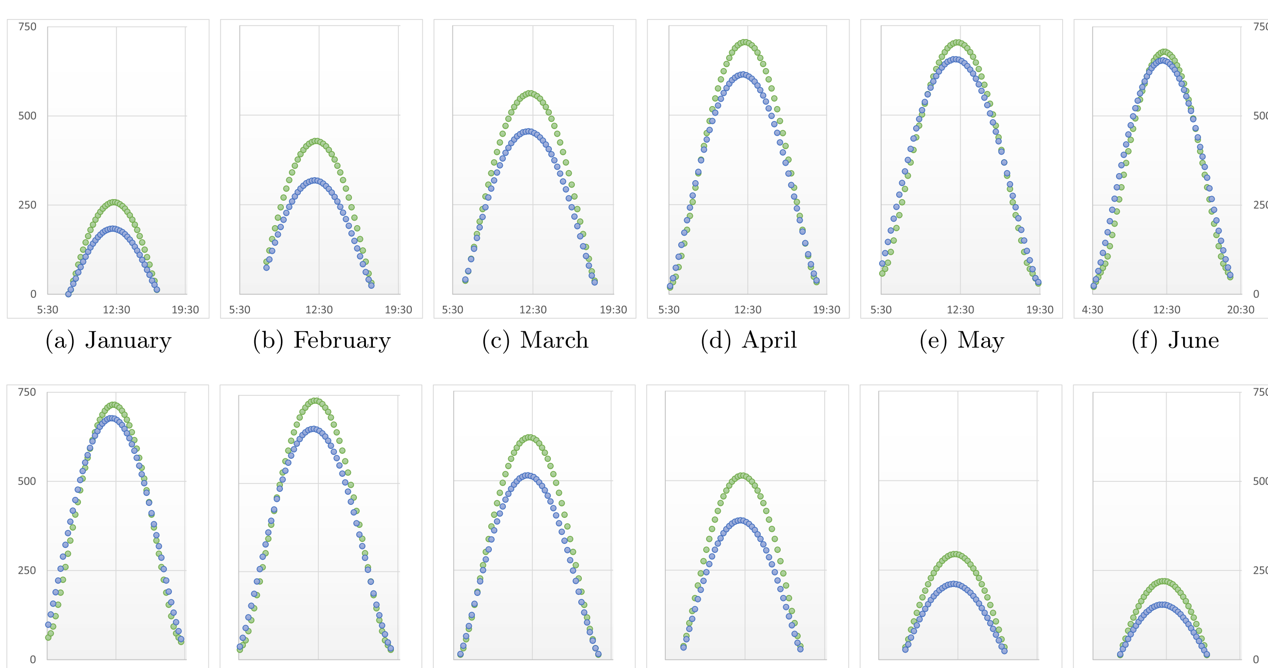
It is interesting to analyze how alterations in the PV system installation affects the average daily energy production profile in each month. These profiles are presented in Fig. 6 both for the ’optimal’ installation (100%) and the ‘90%’ installation that enhances complementarity.

The aforementioned ’relocation’ of energy production is also witnessed in these figures. Indeed, solar PV energy output slightly increases in summer and significantly decreases in winter. In addition to that the analysis of Fig. 6 reveals a differentiation of energy production over time, during the typical day of each month. Thus, in this case study an increase in the complementarity results in the energy production increasing in early morning between April and August and have lower values in the remaining months (Fig. 6). This is due to the orientation of the PV modules slightly towards east. In the absence of significant shadowing the complementarity will not depend on whether the azimuth of the modules is towards east or west, due to the fact that the complementarity is calculated on a monthly basis. Thus, the choice of azimuth could be made using other criteria, such as improving the fit of the production curve with the electricity consumption pattern in the area surrounding the installation.

6. Conclusions

The effective integration of RES in existing energy systems also depends on the design of RES with ‘smoother’ energy production. The proposed methodology supports estimations on the complementarity between SHPS and solar systems and suggests possible alterations on the systems' design that increase their complementarity over time. Moreover, it offers estimations on the trade-off between solar energy compromises and increases of complementarity. In the studied location a 10% compromise in the energy output of the SPVS results to a significant increase of the complementarity between SHPS and SPVS (correlation coefficient $\simeq -66.4\%$). This latter characteristic can be a supportive tool for system-developers and help them estimate the ’price’ of different levels of increase in the complementarity.

Obviously the status of complementarity, its characteristics and



(a) January (b) February (c) March (d) April (e) May (f) June
(g) July (h) August (i) September (j) October (k) November (l) December

Fig. 6. Daily solar irradiance (W/m^2) profiles for two installation options throughout the year: 100% (green) – 90% (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the degree that it can be increased depend largely on local conditions. The authors plan to further investigate possible reductions of intermittency by including the spatial aspect in future analysis. This includes experiments on possible alterations of the PV systems' location that might benefit the complementarity with the SHP. Another aspect is related to areas with different climate characteristics (temperature, precipitation) and accordingly different stream flow profiles. It is important to study the diverse seasonal variations of water discharge in different geographical regions and how such differentiation affect the complementarity between SHPS and SPVS.

It is interesting to note that currently don't exist any incentive policies and motives to increase the complementarity of renewable energy systems. In case of systems connected to the grid Feed-in Tariffs, Net-metering schemes act as financial instruments that support the systems according to the quantity of the produced energy. Considering that the proposed approach requires a 'sacrifice' on the energy output, it appears that the existing incentive schemes can discourage the development of systems with enhanced complementarity. On the contrary, stand-alone systems and isolated mini grids can benefit from the optimization of the complementarity by reducing the cost of energy storage. Accordingly, the required battery capacity or the operation of back-up diesel gensets will be reduced, with obvious benefits on the cost.

Disclaimer

The views expressed in this paper are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

References

[1] IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment, Intergover Edition, Geneva, Switzerland, 2014. http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR/_AR5/_FINAL/_full.pdf.

[2] IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation, 2012. http://www.ipcc.ch/pdf/special-reports/srren/SRREN/_Full/_Report.pdf.

[3] U.-S. Energy & Commerce Committee, Hydropower Regulatory Efficiency Act, 2013. http://www.ferc.gov/legal/fed-sta/bills-113hr267enr.pdf.

[4] European Council, 2030 Climate and Energy Policy Framework, 2014. http://ec.europa.eu/clima/policies/2030/index/_en.htm.

[5] K. Bódis, F. Monforti, S. Szabó, Could Europe have more mini hydro sites? A suitability analysis based on continentally harmonized geographical and hydrological data, Renew. Sustain. Energy Rev. 37 (2014) 794–808, http://dx.doi.org/10.1016/j.rser.2014.05.071. http://dx.doi.org/10.1016/j.rser.2014.05.071.

[6] F. Monforti, T. Huld, K. Bódis, L. Vitali, M. D'Isidoro, R. Lacal-Arántegui, Assessing complementarity of wind and solar resources for energy production in Italy. A Monte Carlo approach, Renew. Energy 63 (2014) 576–586, http://dx.doi.org/10.1016/j.renene.2013.10.028. http://dx.doi.org/10.1016/j.renene.2013.10.028.

[7] S. Spiecker, C. Weber, The future of the european electricity system and the impact of fluctuating renewable energy - a scenario analysis, Energy Policy 65 (2014) 185–197, http://dx.doi.org/10.1016/j.enpol.2013.10.032. http://dx.doi.org/10.1016/j.enpol.2013.10.032.

[8] C. Hoicka, I. Rowlands, Solar and wind resource complementarity: advancing options for renewable electricity integration in Ontario, Can. Renew. Energy 36 (1) (2011) 97–107, http://dx.doi.org/10.1016/j.renene.2010.06.004. http://dx.doi.org/10.1016/j.renene.2010.06.004.

[9] J. Kenfack, F.-P. Neirac, T.-T. Tatietse, D. Mayer, M. Fogue, A. Lejeune, Microhydro-PV-hybrid system: sizing a small hydro-PV-hybrid system for rural electrification in developing countries, Renew. Energy 34 (2009) 2259–2263, http://dx.doi.org/10.1016/j.renene.2008.12.038.

[10] M. Santarelli, S. Macagno, Hydrogen as an energy carrier in stand-alone applications based on PV and PV-micro-hydro systems, Energy 29 (2004) 1159–1182, http://dx.doi.org/10.1016/j.energy.2004.02.023.

[11] S. Ashok, Optimised model for community-based hybrid energy system, Renew. Energy 32 (2007) 1155–1164, http://dx.doi.org/10.1016/j.renene.2006.04.008.

[12] E.M. Nfah, J.M. Ngundam, Feasibility of pico-hydro and photovoltaic hybrid power systems for remote villages in Cameroon, Renew. Energy 34 (6) (2009) 1445–1450, http://dx.doi.org/10.1016/j.renene.2008.10.019. http://dx.doi.org/10.1016/j.renene.2008.10.019.

[13] G. Bekele, G. Tadesse, Feasibility study of small hydro/pv/wind hybrid system for off-grid rural electrification in Ethiopia, Appl. Energy 97 (2012) 5–15, http://dx.doi.org/10.1016/j.apenergy.2011.11.059. http://dx.doi.org/10.1016/j.apenergy.2011.11.059.

[14] A. Beluco, P. Kroeff de Souza, A. Krenzinger, A dimensionless index evaluating the time complementarity between solar and hydraulic energies, Renew. Energy 33 (2008) 2157–2165, http://dx.doi.org/10.1016/j.renene.2008.01.019.

[15] A. Beluco, P. Kroeff de Souza, A. Krenzinger, A method to evaluate the effect of complementarity in time between hydro and solar energy on the performance of hybrid hydro PV generating plants, Renew. Energy 45 (2012) 24–30, http://dx.doi.org/10.1016/j.renene.2012.01.096. http://dx.doi.org/10.1016/j.renene.2012.01.096.

[16] F.J. Santos-Alamillos, D. Pozo-Vázquez, J. Ruiz-Arias, L. Von Bremen, J. Tovar-Pescador, Combining wind farms with concentrating solar plants to provide stable renewable power, Renew. Energy 76 (2015) 539–550, http://dx.doi.org/10.1016/j.renene.2014.11.055. http://www.sciencedirect.com/science/article/pii/S096014811400785X.

[17] N. S. Thomaidis, F. J. Santos-Alamillos, D. Pozo-Vázquez, J. Usaola-García, Optimal management of wind and solar energy resources, Computers & Operations Research, doi:10.1016/j.cor.2015.02.016. URL http://linkinghub.elsevier.com/retrieve/pii/S0305054815000556.

[18] P.S. dos Anjos, A.S.A. da Silva, B. Stošić, T. Stošić, Long-term correlations and cross-correlations in wind speed and solar radiation temporal series from Fernando de Noronha Island, Brazil, Phys. A Stat. Mech. Appl. 424 (2015) 90–96, http://dx.doi.org/10.1016/j.physa.2015.01.003. http://linkinghub.elsevier.com/retrieve/pii/S0378437115000059.

[19] I. Kougias, N. Theodossiou, Application of the harmony search optimization algorithm for the solution of the multiple dam system scheduling, Optim. Eng. 14 (2) (2013) 331–344, http://dx.doi.org/10.1007/s11081-011-9183-x.

[20] V. H. Ho, I. Kougias, J. H. Kim, Reservoir Operation using hybrid optimization algorithms, Global NEST Journal 17(1). URL http://journal.gnest.org/sites/default/files/Submissions/gnest_01461/gnest_01461_proof.pdf.

[21] J.S. Gulliver, R.E. Arndt, Hydropower Engineering Handbook, McGraw-Hill, 1991.

[22] I. Kougias, D. Karakatsanis, A. Malatras, N. Theodossiou, Developing a harmony-based optimization toolbox: application on renewable energy production, in: OPT-I Conference on Engineering & Applied Sciences Optimization, 2014, pp. 1017–1030.

[23] R. Müller, C. Matsoukas, A. Gratzki, H. Behr, R. Hollmann, The CM-SAF operational scheme for the satellite based retrieval of solar surface irradiance - a LUT based eigenvector hybrid approach, Remote Sens. Environ. 113 (5) (2009) 1012–1024, http://dx.doi.org/10.1016/j.rse.2009.01.012.

[24] T. Huld, R. Müller, A. Gambardella, A new solar radiation database for estimating PV performance in Europe and Africa, Sol. Energy 86 (2012) 1803–1815, http://dx.doi.org/10.1016/j.solener.2012.03.006.

[25] T. Muneer, Solar radiation model for Europe, Build. Serv. Eng. Res. Technol. 11 (4) (1990) 153–163, http://dx.doi.org/10.1177/014362449001100405.

[26] N. Martin, J. Ruiz-Arias, Calculation of the PV modules angular losses under field conditions by means of an analytical model, Sol. Energy Mater. Sol. Cells 70 (1) (2001) 25–38, http://dx.doi.org/10.1016/S0927-0248(00)00408-6. http://www.sciencedirect.com/science/article/pii/S0927024800004086.

[27] D. Faiman, Assessing the outdoor operating temperature of photovoltaic modules, progress in photovoltaics, Res. Appl. 16 (4) (2008) 307–315, http://dx.doi.org/10.1002/pip.813. http://onlinelibrary.wiley.com/doi/10.1002/pip.813/abstract.

[28] M. Koehl, M. Heck, S. Wiesmeier, J. Wirth, Modeling of the nominal operating cell temperature based on outdoor weathering, Sol. Energy Mater. Sol. Cells 95 (7) (2011) 1638–1646, http://dx.doi.org/10.1016/j.solmat.2011.01.020. http://www.sciencedirect.com/science/article/pii/S0927024811000304.

[29] T. Huld, G. Friesen, A. Skoczek, R. Kenny, T. Sample, M. Field, E. Dunlop, A power-rating model for crystalline silicon PV modules, Sol. Energy Mater. Sol. Cells 95 (12) (2011) 3359–3369, http://dx.doi.org/10.1016/j.solmat.2011.07.026. http://www.sciencedirect.com/science/article/pii/S0927024811004442.

[30] J.D. Mondol, Y.G. Yohanis, B. Norton, The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system, Renew. Energy 32 (2007) 118–140, http://dx.doi.org/10.1016/j.renene.2006.05.006.